# A Joint Power Control and Routing Scheme for Rechargeable Sensor Networks

Amitangshu Pal and Asis Nasipuri
Electrical & Computer Engineering, The University of North Carolina at Charlotte, Charlotte, NC 28223-0001
E-mail:{apal,anasipur}@uncc.edu

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***Abstract-* We propose a joint power control and quality aware routing scheme for rechargeable wireless sensor networks (WSNs) in order to achieve reliable network operation in the presence of spatial and temporal variations of energy resources. The proposed scheme reduces the energy consumption in sensor nodes that have low remaining battery life through cooperative and network-wide adaptations of transmit power levels and parent selection. The proposed approach incorporates estimated remaining lifetimes of nodes, the predicted minimum power levels for achieving reliable link quality, and a routing metric that includes the effect of overhearing caused to nodes that are critically low in energy resources, in addition to route quality. Performance evaluations are presented from extensive simulation studies to show the effectiveness of the proposed scheme.**

***Keywords:* Wireless sensor networks, power controlled routing, distributed algorithms.**

## I. Introduction

Powering wireless sensor nodes with energy harvested from the environment, such as solar, mechanical, thermal, and others, is an effective approach for achieving long-term maintenance-free operation of wireless sensor networks (WSN). Although a variety of energy harvesting devices for low-power electronic equipment are available [1], [2], [3], [4], a key challenge for achieving reliable and uninterrupted operation of WSNs powered by such renewable energy sources is to adequately address the variability of the energy harvested from these devices. Renewable energy such as solar can have wide spatial and temporal variations due to natural (e.g. weather) and location specific factors (e.g. exposure to sunlight) that can be difficult to predict prior to deployment. In addition, due to cost and size restrictions, wireless sensor nodes are not expected to have energy harvesting units that can achieve the minimum energy requirements under all environmental conditions. Consequently, WSNs powered by energy harvested from renewable energy sources can suffer from frequent and unpredictable node outages that can seriously affect the monitoring operations of the network. An effective approach for addressing this problem is to design network protocols and processing schemes that enable the nodes to dynamically adapt their energy consumption based on estimated energy resources, which is the main objective of this work.

We consider WSNs that are applied for environmental monitoring applications, typically using periodic transmissions of sensor observations to a centralized base station. For such data collection traffic, routing protocols such as the *Collection Tree Protocol (CTP)* [5] with low-power listen provides an effective solution for energy-efficient network communications. However, since it is difficult to achieve tight network synchronization in such networks, especially when the network size is large, *overhearing* contributes to a large amount of energy consumption in such networks [6], [7]. A practical approach for reducing overhearing is by reducing the neighborhood size of the nodes using transmission power control. Although a significant amount of work has been reported on power control for WSNs, most of it has been directed towards reducing interference effects for improving the communication performance in the network [8], [9]. Here, our objective is apply power control to achieve energy conservation by reducing overhearing. The main challenge for using power control for reducing overhearing is that the degree of overhearing at a node depends on the transmit power levels and traffic of its *neighbors*. Consequently, effective overhearing control requires *network wide* adaptations of transmit power levels as well the distribution of data traffic in the nodes as opposed to independent adaptations at the nodes.

In our earlier work [10], we proposed a distributed power control and routing scheme for a WSN of rechargeable nodes, where nodes are assumed to have varying amounts of energy resources. The proposed adaptation algorithm is based on each node determining requirement for energy conservation from its estimated energy resources (battery life) and average energy consumption from periodic assessments. This information is broadcast to its neighbors for consideration of their power control. The power control mechanism also takes into consideration the *ETX* values used in the applied *CTP* routing protocol. In this report, we extend that work to implement a *joint* power control and routing scheme for rechargeable sensor networks. The current work introduces two new ideas for implementing power control and routing for adaptive overhearing control. First, we introduce a prediction model that is applied by each node to determine the extent by which it can reduce its power for achieving an acceptable probability of success in data packet delivery to its parent. Secondly, we incorporate a parameter that represents the level of overhearing caused by transmission along a path to those nodes that need overhearing control, i.e. have critically low energy resources.

The rest of the report is organized as follows. In section II, we present some preliminary concepts related to data collecting WSNs that are relevant for this work. In section III we discuss the prediction model that is applied for power control. The proposed joint power control and routing scheme is presented in section IV. Performance evaluations of our proposed scheme obtained from simulation experiments are discussed in section V. We conclude our paper section VI.

## II. Preliminaries

We assume a WSN where the nodes have dissimilar battery capacities, representing a typical scenario where each node has different amounts of energy resources as harvested from the environment. We define the battery *health-metric* $H$ of a node to represent its remaining battery lifetime, i.e. the estimated time until its battery is depleted under its currently estimated energy usage. We assume $H \propto \frac{B}{\mathcal{I}}$, where $B$ is the remaining capacity of the battery and $\mathcal{I}$ represents the estimated current drawn at the node. Based on the experimentally validated model [11], the current drawn in each node is calculated as follows:

$$\begin{aligned} \mathcal{I} &= \tfrac{I_{Bt}T_{Bt}}{T_B} + M.I_{Dt}T_{Dt} + N.\tfrac{I_{Br}T_{Br}}{T_B} + O.I_{Dr}T_{Dr} \\ &+ F.I_{Dt}T_{Dt} + \tfrac{I_s T_s}{T_D} + N_P.I_P T_P \end{aligned} \quad (1)$$

where $I_x$ and $T_x$ represent the current drawn and the duration, respectively, of the event $x$; and $T_B$ represents the beacon interval. Transmission/reception of beacons is denoted by $B_t/B_r$, data transmit/receive is denoted by $D_t/D_r$ and processing and sensing are denoted as $P$ and $S$, respectively. $O$ and $F$ are the overhearing and forwarding rates, respectively, and $N$ is the number of neighbors. $M$ is the rate at which a node transmits its own packets. If there are no retransmissions, then $M = \frac{1}{T_D}$, where $T_D$ is the data interval. $N_P$ represents the number of times that a node wakes per second to check whether the channel is busy, and is set to 8 in our application. We assume that each node is able to estimate all the dynamic parameters that are used in equation (1), by periodic assessment of its overheard and forwarded traffic.

The battery capacity $B$ (energy resource) depends on a number of factors that include the solar irradiance, the efficiency of the solar panel, the efficiency of the converter circuit, as well as physical and environmental factors such as temperature and state of health of the battery or storage element. An appropriate model for estimating the battery state of charge is currently being developed by the researchers, and will be included in future work. For the development and evaluation of the power control and routing scheme for adapting the energy consumpiton at the nodes to their battery health, we assume that the battery capacity is obtanied from battery voltage. To further simplify the task of estimating $B$, we apply a linear relationship between the battery voltage and $B$, which is explained later.[1]

To estimate the quality of a route, we use the *expected number of transmissions (ETX)* that is used in *Collection Tree Protocol (CTP)* which is discussed below. An ETX is the expected number of transmission attempts required to deliver a packet successfully to the receiver. Hence, a low ETX value indicates a good end to end quality of a route, and vice versa. In our scheme, ETX is calculated similar to [5].

CTP is a tree based collection protocol whose main objective is to provide best effort anycast datagram communication to one of the collection root nodes in the network. At the start of the network some of the nodes advertise themselves as the root nodes or sink nodes. The rest of the nodes use the root advertisements to connect to the collection tree. When a node collects any physical parameter, it is sent up the tree. As there can be multiple root nodes in the network, the data is delivered to one with the minimum cost. CTP is an *address free protocol*, so a node does not send the packet to a particular node but chooses its next hop based on a routing gradient. CTP uses ETX as its routing gradient as mentioned earlier. The sink always broadcasts an ETX = 0. Each node calculates its ETX as the ETX of its parent plus the ETX of its link to the parent. This measure assumes that nodes use link-level acknowledgements and retransmissions. A node $i$ chooses node $j$ as its parent among all its neighbors if $\text{ETX}_{ij}$+ETX of $j <$ $\text{ETX}_{ik}$+ETX of $k\, \forall k \neq j$, where $\text{ETX}_{ij}$ and $\text{ETX}_{ik}$ are the ETX of link $i \to j$ and $i \to k$ respectively. A node using CTP chooses the route with the lowest ETX value to the sink.

## III. Prediction Model for Estimating Transmission Power Levels

We propose to apply prediction using an experimentally validated model for determining the probability of successful packet delivery over a link for any transmit power level. We observe that the packet delivery ratio (PDR) of a link follows a sigmoid curve (Q-function) with the transmit power level. This can be derived as follows.

$$\begin{aligned} PDR &= Prob\,[P_r(d) > \gamma] = Prob\,[P_t - P_l(d) > \gamma] \\ &= Prob\left[P_t - \overline{P_l(d)} + X_\sigma > \gamma\right] \\ &= Q\left(\frac{\gamma - P_t + \overline{P_l(d)}}{\sigma}\right) \end{aligned} \quad (2)$$

where $P_t$ is the transmit power, $P_r(d)$ and $P_l(d)$ are the power received and path loss at distance $d$, $\gamma$ is the threshold for minimum received signal level at the received. $X_\sigma$ is a Gaussion random variable with zero-mean and standard deviation of $\sigma$.

The design objective is to establish a model that reflects the correlation between transmission power and packet delivery

[1] Note that the battery voltage does not accurately reflect its state of charge, however, it is a simple way to obtain an approximate measure of the level of charge in a battery.

ratio of a link. Based on this model we can predict the transmission power level required to ensure a required link quality. In addition, the model can be applied to determine if it will cause overhearing to specific neighbors. Note that overhearing is really a physical layer phenomenon; however, the amount of overhearing can be estimated from the number of received packets as observed at the network layer. Also the link quality (also ETX) corresponding to any transmit power will be used to measure the ETX of any node.

The idea of this prediction model is to use a sigmoid function to approximate the distribution of delivery ratio at different transmission power levels, and to adapt to the environment changes by modifying the function over time. The function is constructed from sample pairs of transmission power levels and delivery ratios using a linear regression curve-fitting approach. To obtain these samples, all nodes overhear the packets of their neighbors, use curve-fitting to model each link and broadcast these coefficients using periodic beacon messages. This scheme does not incur any additional overheads other than periodic beacon messages. Becaons messages are sent with highest power so that all neighboring nodes can receive them.

As the delivery ratio (assume $p$) can be modellled as a sigmoid function of transmit power (assume $t$), then

$$\begin{aligned} p &= \frac{1}{1+e^{-(a.t+b)}} \\ a.t+b &= log_e\left(\frac{p}{1-p}\right) \\ &= P \text{ (say)} \end{aligned} \tag{3}$$

The variation of delivery ratio with transmit power is shown in Fig 2. We formulate this predictive model in the following way, which uses two vectors $\mathcal{T}$ and $\mathcal{P}$. $\mathcal{T}$ contains all transmission power levels, thus $\mathcal{T} = \{t_1, t_2, ..., t_N\}$. The vector $\mathcal{P}$ contains all the $log_e\left(\frac{p}{1-p}\right)$ terms, i.e. $\mathcal{P} = \{P_1, P_2, ..., P_N\}$. Thus, expressing equation (3) in matrix form we get

$$\begin{aligned} \begin{bmatrix} t_1 & 1 \\ \vdots & \vdots \\ t_N & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} &= \begin{bmatrix} P_1 \\ \vdots \\ P_N \end{bmatrix} \\ \Rightarrow a &= \frac{\sum P_i . \sum t_i - m . \sum t_i . P_i}{\sum t_i . \sum t_i - m . \sum t_i^2} \\ \Rightarrow b &= \frac{\sum P_i - a . \sum t_i}{m} \end{aligned} \tag{4}$$

This is to be noted that $a$ and $b$ is a function of time, each node keeps on updating these values and broadcasts them using beacon messages. Here we need to mention three points which is important corresponding to this prediction model. First, this prediction model works well when the sampling data points are more. Thus the prediction model is used only when a node gets enough confidence over a link, i.e. if it receives enough data packets of different power levels and the delivery ratio corresponding to the lower transmit power is less than some threshold (as sigmoid is a S-shaped function). Second, this prediction model is receiver-oriented as shown in Fig 2(a). The receiver receives or overhears the packets transmitted by the sender in different power levels, keeps and updates the $(t, P)$ pairs corresponding to each power level and calculates coefficients $a$ and $b$ if it has enough $(t, P)$ pairs. The coefficients $a$ and $b$ is broadcasted along with the sender ID with the beacon messages. If the receiver does not have enough $(t, P)$ pairs, it simply broadcasts $a$ and $b$ with their default values. The transmitter uses this coefficients to predict the link quality to that receiver for any power level. Third, beacons are transmitted periodically with the highest transmit power. Note that in this scheme a node apends the coefficients and the neighbor ID corresponding to each neighbor in its beacon message. If a node has a large number of neighbors, this scheme increases the packet size. To restrict the beacon message size, in our scheme a node appends $n$ (we assume $n$ to 3) neighbor's ID and coefficients in each beacon. Thus the neighbor IDs as well as their coefficients are appended in a round-robin fashion, each time for $n$ neighbors.

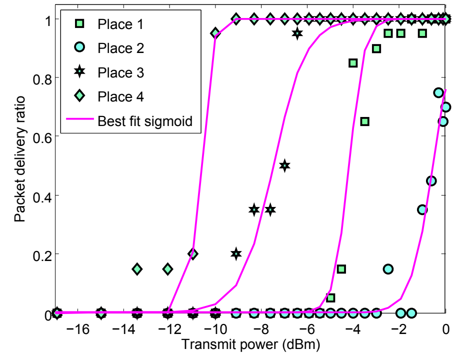


Fig. 1. Sigmoid best fit curve of delivery ratio vs transmit power.

## IV. The Proposed Joint Power Control and Routing Scheme

We now present the proposed joint power control and routing scheme for WSNs that mainly tries to fulfill two objectives. First, it reduces overhearing on *critical nodes*, which are nodes that have battery health lower than average. This will extend the overall lifetime of the network. Second, routes are adapted dynamically and in a distributed fashion to avoid regions that are in shadows, which reduces forwarding and overhearing rates on the nodes in shadowed regions. All nodes periodically determine their parents as well as transmit powers based on their neighboring link qualities and their neighbors health metrics. We assume that all nodes broadcast periodic beacon messages, which include their node ID, ETX value and a field named *critical node (CN)* which is 1 if a node is critical and 0 otherwise. Also the beacon message carries another field named *probability of control (POC)* which is explained later. Besides that a beacon message includes $n$ neighbor IDs, their corresponding coefficients and the current forward-ETX ($\text{ETX}_F$) of the link from its neighbor to itself, as well as its current transmit power level. $\text{ETX}_F$ is set to its maximum value if a node does not have an entry corresponding to the

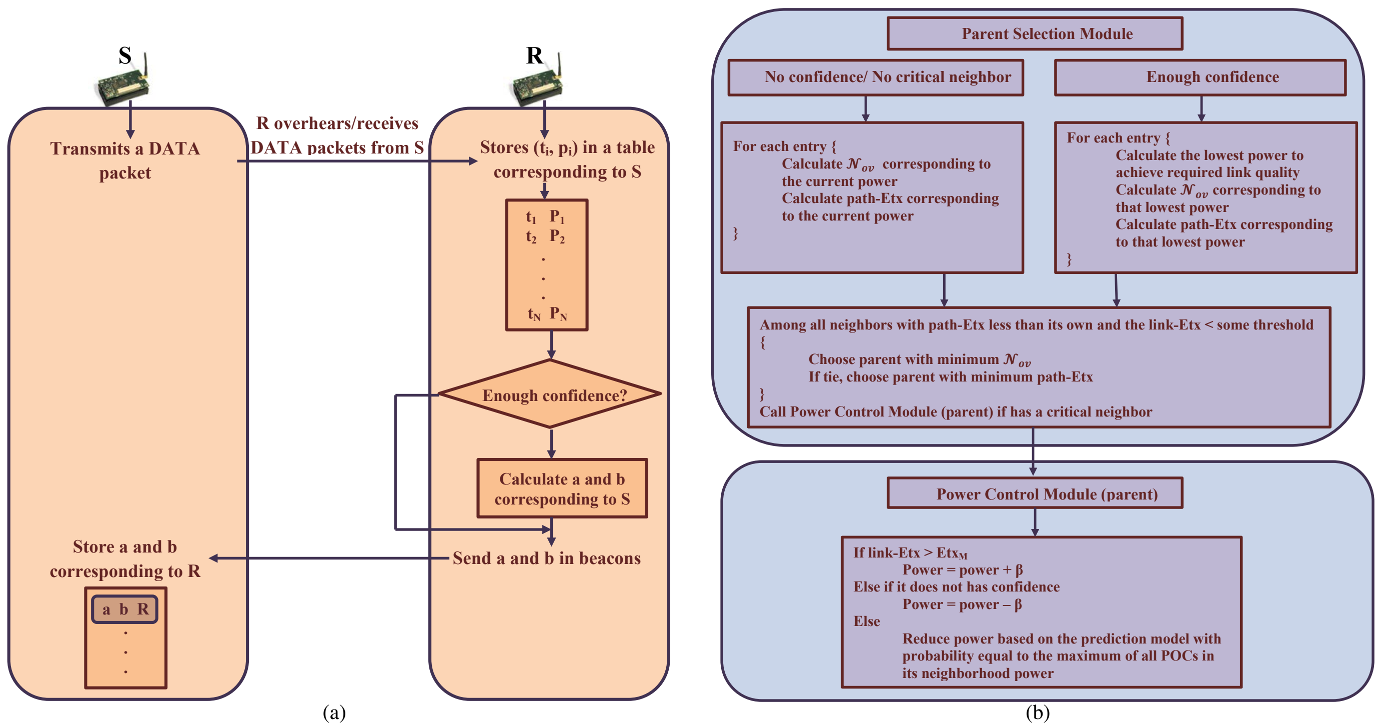


Fig. 2. (a) Receiver-oriented prediction model. (b) Proposed joint power control and routing scheme.

current power level of its neighbor. For the sake of simplicity, we explain the power control and parent selection separately as follows. Even if power control and parent selection are described separately, these are done jointly as explained later.

### *A. Power Control*

We define a node as critical node if its $H < \alpha.\mu_H$, where $\mu_H$ is the mean of its neighbors health metrics. It then makes the POC = $\frac{\mu_H - H}{\mu_H}$. Otherwise, the node is considered as good node and POC = 0 for all good nodes. The parameter POC is mainly used by a critical node to inform its neighbors how critical the node is. If a node's condition is very critical, it broadcasts a high POC. So its neighbors reduce their transmit power with high probability. The reverse happens when a node is less critical.

If a node is not in a critical stage, it broadcasts beacons with CN = 0 and everything works same as CTP. The parent is selected as the neighbor with lowest ETX and is done periodically. The power adaptation does not take place in this case.

When a node becomes critical, it broadcasts its beacon message with CN = 1. Nodes that receive a beacon with CN = 1 adapt their transmit power as follows:

*Reduce transmit power in steps:* When a nodes receives coefficients $a$, $b$ with their default values corresponding to any neighbor, it reduces transmission power in steps, i.e. by $\beta$ with probability = 1, if its link-ETX is less than some threshold $\mathrm{ETX}_m$ and its current transmit power is more than a minimum level. Link-ETX of a node is defined as the ETX of the link between that node and its parent. The reason for reducing transmit power with probability = 1 is to let its neighbors to get enough $(t, P)$ pairs so that they can make the prediction model described earlier.

*Reduce transmit power using prediction model:* If a node receives the coefficients with any non-default values it uses the prediction model to reduce its power. In that case the node uses transmit power $t$ such that $t$ is the minimum transmit power of achieve a delivery ratio greater than some threshold required to maintain a minimum link quality. If it receives beacon messages from multiple critical nodes, the power is reduced with probability equal to the maximum of all POCs of the critical nodes. This results in reduced overhearing on the critical nodes.

*Increase power:* Also if the link-ETX of any node goes beyond a threshold $\mathrm{ETX}_M$, nodes start increasing power in steps of $\beta$.

### *B. Routing*

As the change in transmit power affects the ETX, parent selection is tied to power control. Here we introduce a parameter $p_{ov}$, which is the probability that the node overhears the neighboring node with maximum POC. The sink broadcasts beacons with $\mathcal{N}_{ov} = F.p_{ov} = 0$. $\mathcal{N}_{ov}$ is basically the number of packets overheard by the worst critical neigbor of a test node. Each node calculates and broadcasts its $\mathcal{N}_{ov}$ as the $\mathcal{N}_{ov}$ of its parent plus its number of transmissions that are overheard by its worst critical neighbor, which we denote as $\mathcal{N}^l_{ov}$. $p^l_{ov}$ is basically the packet delivery ratio which can be measured (i) from the prediction model corresponding to the current power level, if the coefficients corresponding to that node is not set

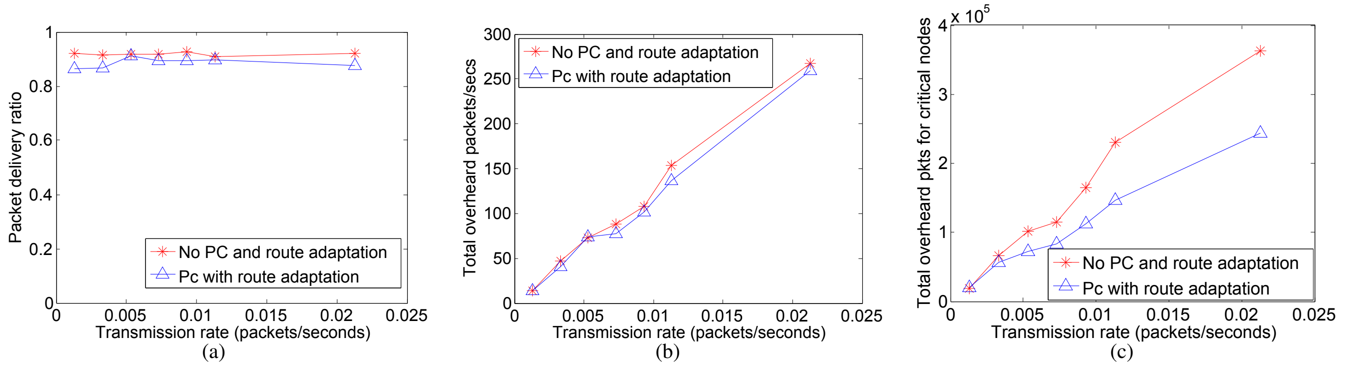


Fig. 3. Comparison of (a) packet delivery ratio (b) network-wide packets overheard (c) packets overheard by the critical nodes with different rates.

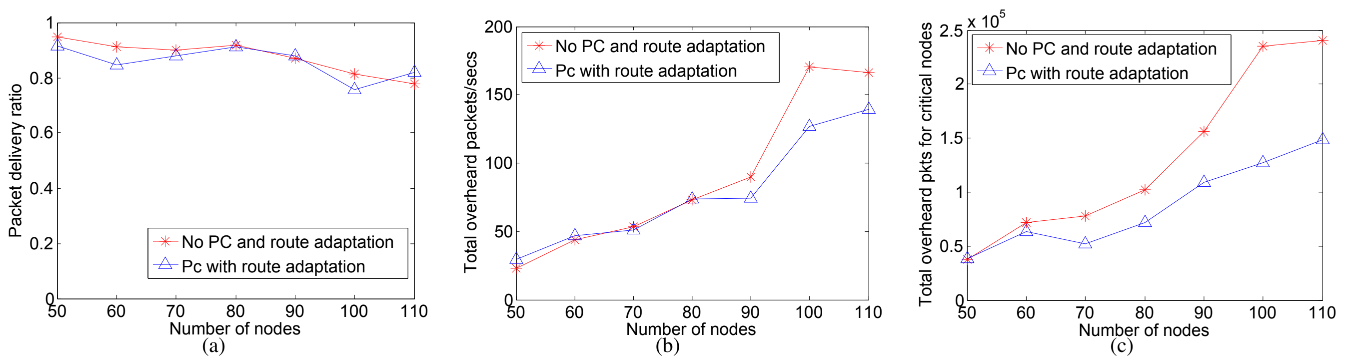


Fig. 4. Comparison of (a) packet delivery ratio (b) network-wide packets overheard (c) packets overheard by the critical nodes with different number of nodes.

to their default values or (ii) from $\text{ETX}_F$ if the coefficients are in their default values.

For each entry in its neighbor table, a node calculates the minimum transmit power required to achieve a minimum link quality from the prediction model if that neighbor send non-default coefficients. Otherwise it considers its current transmit power level. It also calculates the $p^l_{ov}$ of the critical node based on that transmit power and record the metric $\mathcal{N}_{ov}$ which is the sum of that $\mathcal{N}^l_{ov}$ and the $\mathcal{N}_{ov}$ sent by that neighbor. Also it calculates the linkEtx and pathEtx based on that transmit power. It then chooses the entry corresponding to the minimum $\mathcal{N}_{ov}$ among the neighbors that has an ETX less than its own (to avoid routing loop) and has a reasonable link-Etx, as its parent. In case of a tie, it chooses the parent that gives least pathETX. Thus a route with minimum $\mathcal{N}_{ov}$ is the route that overhears the critical nodes with least probability and the route with minimum pathEtx gives the route with minimum cost. Our scheme first tries to choose the route as well as transmit power to achieve minimum $\mathcal{N}_{ov}$ and in case of tie, route with minimum cost is chosen. While choosing its parent in this process, the node determines its transmit power as well, with the probability equal to maximum of all POCs of its critical neighbors. This transmit power and parent selection go on periodically.

Thus we observe that the transmit power control affects the quality metric, which affects the parent selection. Thus the joint power control and routing is achieved that tries to avoid overhearing traffics on critical nodes. The design for our joint power control and route adaptation scheme is depicted in Fig 2(b).

### C. Discussion

Our proposed power controlled routing scheme takes into account a number of factors that are explained as follows:

*Battery state of individual nodes:* The battery state of any node is taken into account by using the term $B$. If the battery condition of any node is bad, its health metric decreases. When it becomes a critical node, its neighbors reduce power with some probability which tries to reduce overhearing on that critical node.

*Reduced load and overhearing on critical nodes:* The term $\mathcal{I}$ calculates the average current consumption of a node. Thus, if a node becomes a critical node due to over-usage, its health metric decreases. So that nodes in its neighborhood reduces power with some probability.

*Route quality:* Also the ETX quantifies how good a route is. The route quality is important as bad routes result in more retransmissions which reduce the network lifetime.

The proposed scheme does not incur any additional control overhead other than periodic beacon updates. Also to avoid *idle listening*, nodes use low-power listening [12] where they sleep most of the time and wakes up in a periodic interval. If they sense the channel to be busy, they remain on. Otherwise, they go back to sleep to conserve energy. Problems such as routing loop detection and repairing are tackled similar to CTP.

## V. Performance Evaluation

This section presents evaluation results of our joint power control and routing scheme from simulations in the *Castalia* simulator [13] where nodes are placed in grid structure in an area of $100 \times 100$ meters. We have chosen 10% nodes to be critical nodes that has lesser capacities as well as receive lesser amount of sunlight compared to others. In this way we try to imitate an actual spatial nature of an outdoor environment. The beacon interval varies between 5 seconds to 50 seconds and the maximum retransmission count is set to 3. Routes are updated in every 8 seconds. At first transmit power is controlled periodically in every 5 minutes. The minimum acceptable delivery ratio is assumed to be 75%. When a node receives confidence for using the sigmoid model, the transmit power is updated along with the route updates. Each simulation is run for around four hours. Parameters used for experiments are listed in Table I.

TABLE I
PARAMETERS USED

| Var | Values | Var | Values | Var | Values | Var | Values |
|---|---|---|---|---|---|---|---|
| $I_{Bt}$ | 20 mA | $T_{Bt}$ | 140 ms | $I_{Br}$ | 20 mA | $T_{Br}$ | 140 ms |
| $I_{Dt}$ | 20 mA | $T_{Dt}$ | 140 ms | $I_{Dr}$ | 20 mA | $T_{Dr}$ | 140 ms |
| $I_P$ | 20 mA | $T_P$ | 7 ms | $I_S$ | 7.5 mA | $T_S$ | 112 ms |

*Comparison with different rates:* Fig 3 shows the variation of the packet delivery ratios, overhearing counts for all the nodes as well as for the critical nodes with different transmission rates, where 80 nodes are placed in a grid. It is observed that the packet delivery ratio is above 90% for all cases. However, overhearing is reduced by nearly 20-25% for the critical nodes when the transmit power is controlled with route adaptation. This clearly shows the effectiveness of our proposed scheme in reducing overhearing on the critical node without affecting the overall packet delivery ratio by a significant amount.

*Comparison with different node density:* Fig 4 shows the variation of the packet delivery ratios, overhearing counts for all the nodes as well as for the critical nodes where the number of nodes are varied from 50 to 110. From this figure also we can observe that with different node densities, the overhearing on the critical nodes are reduced by a significant amount, which validates the effectiveness of our proposed transmit power control and route adaptation scheme.

In both set of graphs we can observe that the overall overhearing is sometimes more and sometimes less compared to the scheme without power control. The reduction in overall overhearing results from reduced transmit power and reduced overhearing on the critical nodes. On the other hand, the increase in transmit power is because of more retransmissions because of reduced transmit power and because of taking deroutes because of avoiding regions that are under shadows. But our main objective is to reduce overhearing on critical nodes, even if overall overhearing increase to reduce the effect of spatial variations of energy availability and consumptions.

## VI. Conclusions and Future Work

In this paper, we propose a distributed scheme for controlling transmit power in a data gathering rechargeable wireless sensor networks for maximizing the network lifetime. Through simulations, we demonstrate that our proposed scheme significantly reduces overhearing on the critical nodes. The proposed scheme has no additional overhead other than periodic beacon updates, which makes it suitable for implementations in real-life applications to prolong the network lifetime.

In future we plan to extend our proposed power control scheme in several directions. First, we will implement an accurate model for estimating the battery state of charge. This is being developed from extensive experimentation and modeling of different battery technologies. In addition, we are researching models for solar irradiance predictions to obtain more realistic assessment of energy variations. Finally we want to implement this scheme in real testbed and evaluate the effectiveness of the proposed scheme.


## Acknowledgement

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